Chapter 23

Deflector Magnet System

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23.1 Introduction

The high energy accelerated beam in an accelerator is scanned over a large area to distribute its energy and utilize the beam for applications. The scanning topology used in EBWWT is two dimensional scanning over an titanium foil window area of 1500 mm × 100 mm. In case the X-X scan magnet fails, the beam will fall on titanium foil till the scan magnet failure is detected and Inverter source to the accelerator is switched off. After inverter is switched off, stored energy in the HV system will be dumped in the Titanium foil, thus raising its local temperature, degrading the vacuum and may lead to foil rupture thus resulting contamination accelerating tubes and electron gun. To prevent this, a deflector magnet is required to deflect the beam as soon as possible after scan magnet failure. The beam is deflected towards scan horn sidewalls (material SS).

23.2 Design Methodology

There was a need of design that would protect the foil under power failure condition as well. Therefore, a compensated magnet was designed as fail safe method. The block diagram for deflector system is shown in Fig. 23.1. The compensated deflector magnet is a dipole magnet consisting of electromagnet and permanent magnets used in flux opposing condition to nullify the field in gap in normal working conditions. But as fault condition of X-magnet failure occurs, two optical signals will be generated, one to switch off the AC source and another to initiate the switching off of electromagnet in the deflector magnet. Switching off electromagnet will result in flux due to permanent magnet to appear in the gap. This will result in deflection of beam to scan horn sides. Total Stored energy in the system = 2 kJ

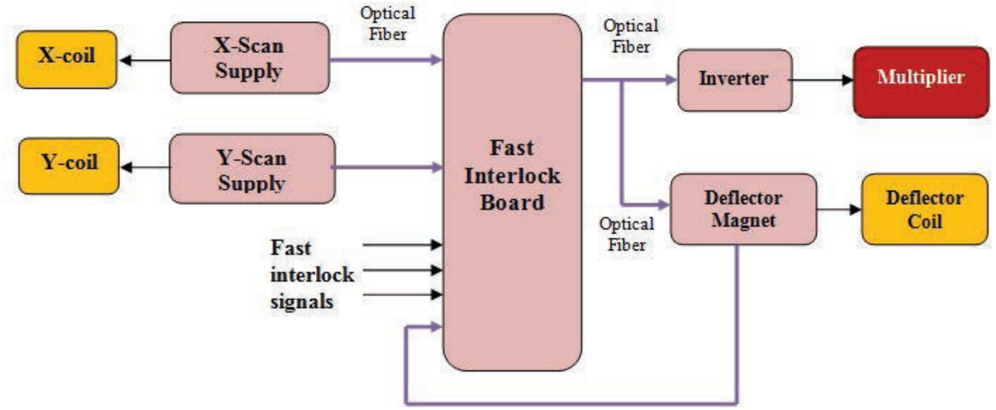


Figure 23.1: System Block diagram.

23.2.1 Temperature Rise Without Deflector Magnet

- Considering the worst case of V = 1 MV, I = 100 mA
- Power loss for 100 mA beam Current (considering 1 keV/μm loss in the foil) = 50 keV × 100 mA = 5 kW
- An estimate energy dumped in Foil in 1 RC time constant (RC constant of the multiplier) = 5 kW × 40 ms = 200 J.

- Temperature rise of Titanium Foil = $\frac{Energy}{mass \times c} = \frac{200\ J}{0.27 \times 0.544} = 1360$ ℃
- Temperature in Degrees = 1360 ℃
- Normal operation Titanium Foil temperature = 200 ℃
- Foil temperature due to dumped energy = (200 + 1360) ℃ = 1560 ℃

23.2.2 Temperature Rise With Deflector Magnet

Considering design value for L/R ratio for the deflector magnet (targeted) = 15 ms So the deflector magnet will start functioning with time constant of 15 ms. Energy loss in Titanium Foil in 15 ms (considering 1 keV/ micron loss in the foil) = 50 keV × 100 mA × 15 ms = 75 J Area covered by the beam in 15 ms is 500 mm of foil, mass for the same is 1.6 kg. Temperature rise of Titanium Foil in 5 ms = $\frac{Energy}{mass \times c} = \frac{75\ J}{1.6 \times 0.544} = 90$ ℃

23.3 Simulation

The deflector was designed for 1 MeV, 100 kW DC accelerator, therefore the simulations studies are accordingly done consideration the mechanical limitations for the magnet. Simulations are done using CST particle studio using core material of Steel 1010 and permanent magnet is defined for NdFeB N35 with B_r of 1.21 T.

Salient Features in the design:

a. Pole Gap requirements come from the Scan Horn width which is 135 mm. Pole gap cannot be smaller than 135 mm.
b. The maximum height for the pole is limited to 70 mm due to mechanical constraint
c. Window Frame magnets cannot be installed. However as window frame magnets give better uniformity therefore the topology are included in studies.

Various load schemes were tried with C-shaped magnet and window frame magnets. Few are discussed.
Let's define few terms for ease of understanding:

- DF_x = Deformity factor in X direction = (X dimension of output Beam - X dimension of input beam)/ (X dimension of input beam)
- DF_y = Deformity factor in Y direction = (Y dimension of output Beam - Y dimension of input beam)/ (Y dimension of input beam)
- D_V = Distortion value = (Maximum change in dimension in any direction)/ (original dimension in that direction).

23.3.1 Window Frame Design-01

Window frame magnets give good uniformity along X direction:

- Magnet size: 400 mm × 250 mm.
- Permanent magnet: 30 mm × 30 mm × 40 mm, NdFeB 1.21 T
- Pole width: 280 mm, shaped Pole.
- Pole height: 70 mm.
- Yoke: 30 mm, yoke height 40 mm.
- Coil: 23.5 A, 250 Turns

Figures 23.2 and 23.3 give the magnet design and field plot.
The Beam qualifying parameters at 1000 mm below magnet:

- DF_x = (10.2-10)/10 = 0.02
- DF_y = (9.75-10)/10 = -0.025

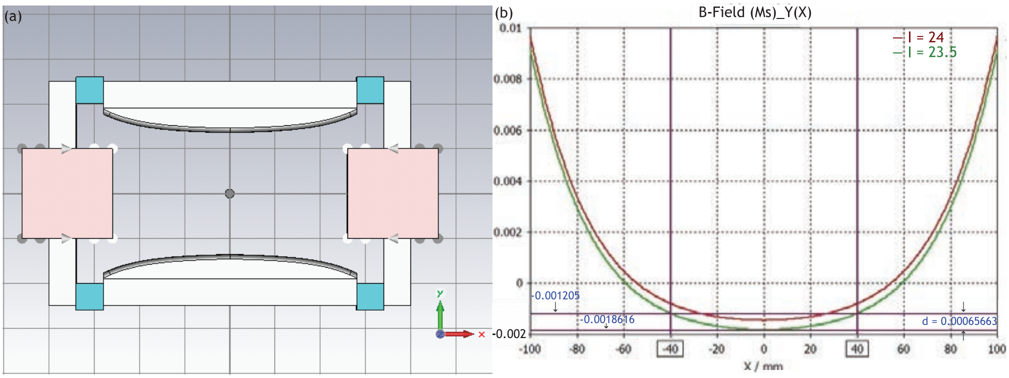


Figure 23.2: (a) Magnet design for window frame magnet with four permanent magnets and shaped pole, and (b) B_y Field at (X, Z) = 0, with zero non-uniformity for -40 mm and 40 mm.

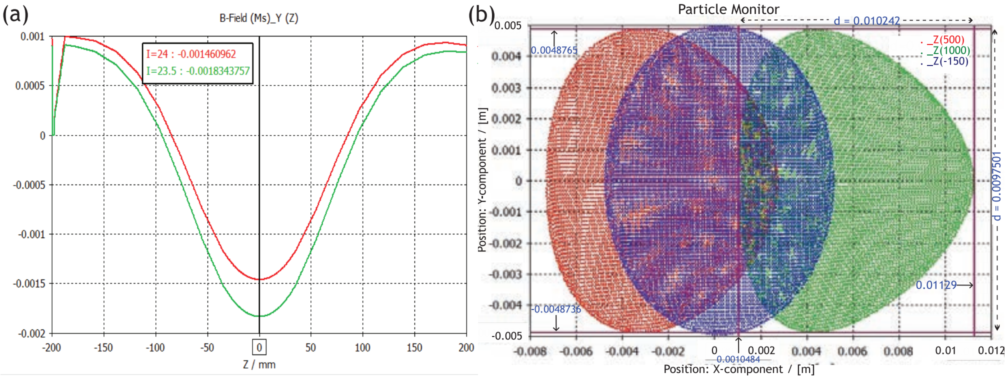


Figure 23.3: (a) B_y Field along Z axis, the center max field for integrated zero field is 23.3 Gauss, and (b) Beam Profile at 1000 mm (green) down from magnet, beam size being 10.2 mm × 9.75 mm.

- $D_V = (9.75\text{-}10)/10 = -0.025$

Conclusion:

- Beam Quality is very good, with 5% non-uniformity
- Ampere Turn requirement is high, 11750 AT

Features:

- Magnet size: 420 mm × 270 mm
- Permanent magnet: 20 mm × 100 mm × 40 mm, NdFeB 1.21 T
- Pole width: 280 mm , shaped Pole
- Pole height: 70 mm
- Yoke: 30 mm, yoke height 40 mm
- Coil: 51 A, 250 Turns, Coil on permanent magnets

23.3.2 Window Frame Design-02

The Figs. 23.4 and 23.5 show the magnet design and field plots.

The Beam qualifying parameters at 1000 mm below magnet:

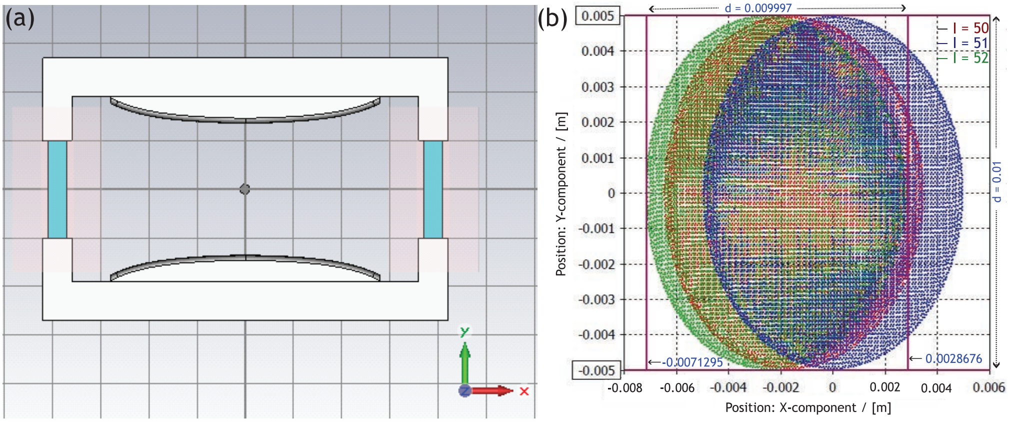


Figure 23.4: (a) Magnet design for window frame magnet with two permanent magnets and shaped pole and coil over permanent magnets, and (b) Beam Profile at 1000 mm (green) down from magnet with beam size of 10 mm × 10 mm.

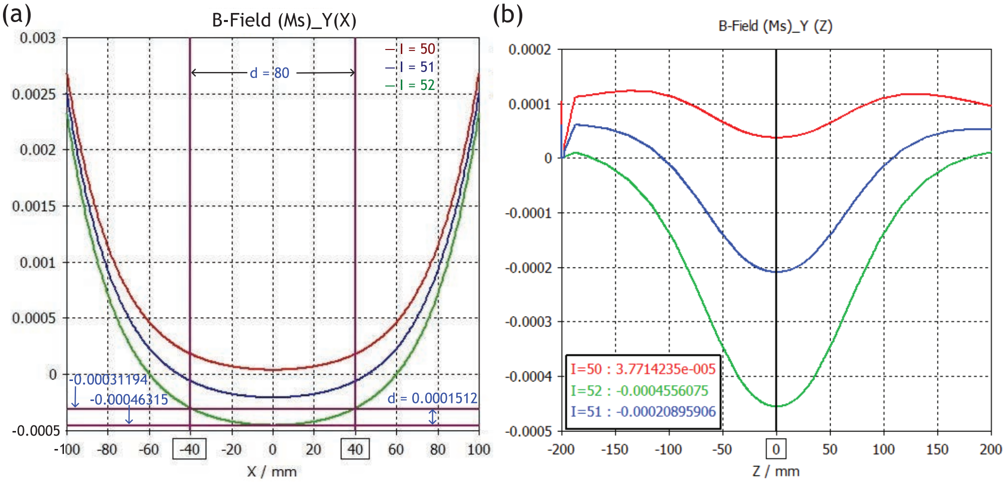


Figure 23.5: (a) B_y Field along X axis for different Ampere Turns, 25500 AT for given 2 Gauss at center, the non-uniformity for -40 mm to 40 mm is 0 Gauss, and (b) B_y Field along Z axis for different Ampere Turns, with 2 Gauss at center to get zero integrated field.

- $DF_x = (10\text{-}10)/10 = 0$
- $DF_y = (10\text{-}10)/10 = 0$
- $D_V = (10\text{-}10)/10 = 0$

Conclusion:

1. Beam Quality is excellent, with 0% non-uniformity
2. Ampere Turn requirement is very high, 25500 AT
3. Field Uniformity is very good

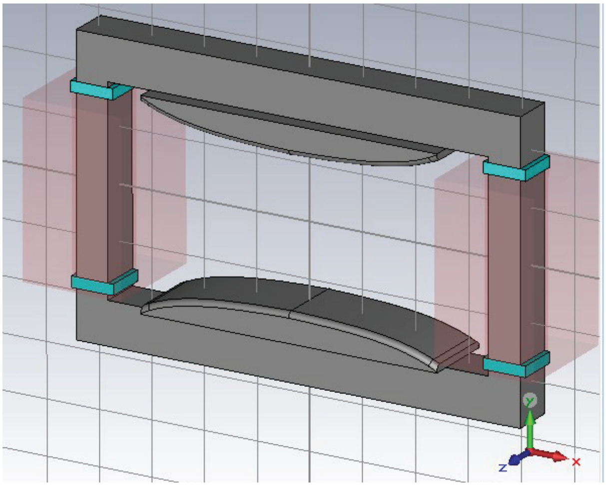
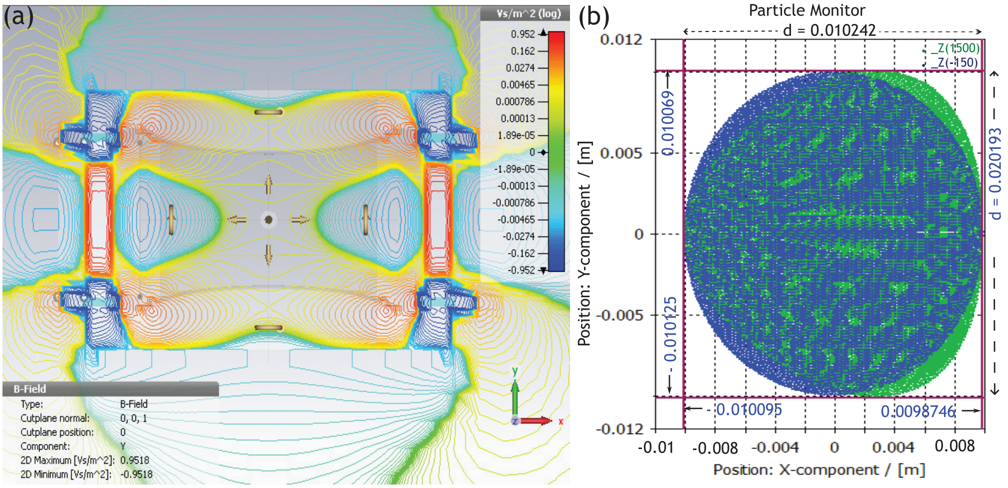


Figure 23.6: Magnet design for window frame magnet with four permanent magnets and shaped pole and coil beside magnets.

23.3.3 Window Frame Design-03

Features:

- Permanent placed just beside coil.
- Yoke width = 30 mm and 40 mm (pole side)
- Yoke height = 40 mm
- Magnet Area = 420 mm × 270 mm
- Pole width = 280 mm, Pole height = 70 mm
- Coil : 250 Turns each, 30.12 A, 15060 AT
- Permanent magnet : 40 mm × 40 mm × 10 mm NdFeB 1.21 T



B-Field
Type: B-Field
Cutplane normal: 0, 0, 1
Cutplane position: 0
Component: Y
2D Maximum [Vs/m^2]: 0.9518
2D Minimum [Vs/m^2]: -0.9518

Figure 23.7: (a) Field Contours for B_y at Z = 0, contours along X axis change the direction of field, and (b) Beam Profile at 1000 mm down the magnet with beam size of 20 mm × 20.2 mm.

The Beam qualifying parameters at 1000 mm below magnet:

- DF_x = (20-20)/20 = 0
- DF_y = (20.2-20)/20 = 0.01
- D_V = (21-20)/20 = 0.05

The Figs. 23.6-23.10 show the magnet design and field plots.

Conclusion:

1. Beam Quality is very good, with almost 2% non-uniformity
2. Ampere Turn requirement is high, 15070 AT
3. Field Uniformity is good

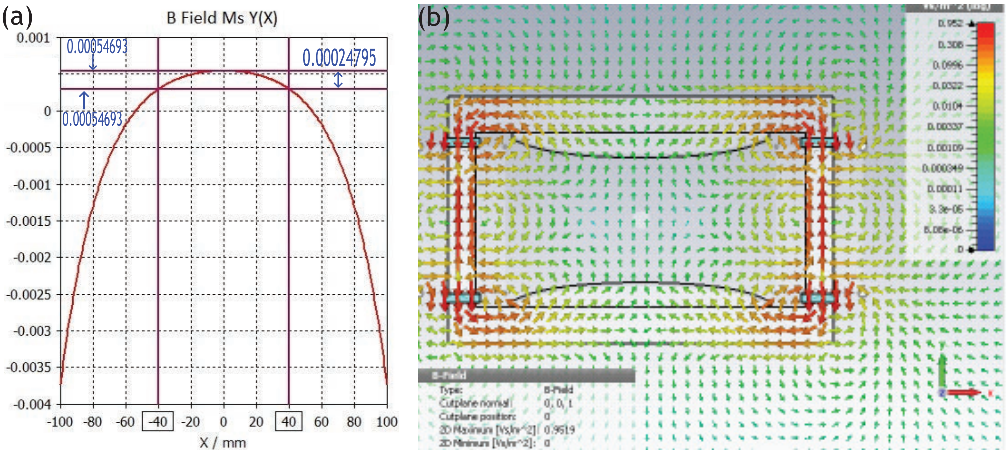


Figure 23.8: (a) B_y Field along X axis for Ampere Turns, 15070 AT for given 5.5 Gauss at center, the non-uniformity for -40 mm to 40 mm is 0 Gauss, and (b) Field lines in compensated condition for X-Y plane.

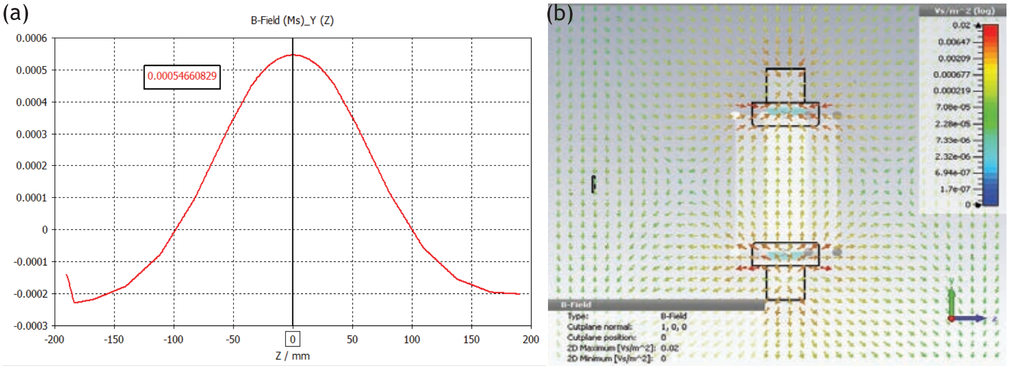


Figure 23.9: (a) B_y Field along Z axis for Ampere Turns, 15070 AT for given 5.5 Gauss at center, and (b) Field lines in compensated condition in for Y-Z plane.

23.3.4 C-Shaped Core-01

Features:

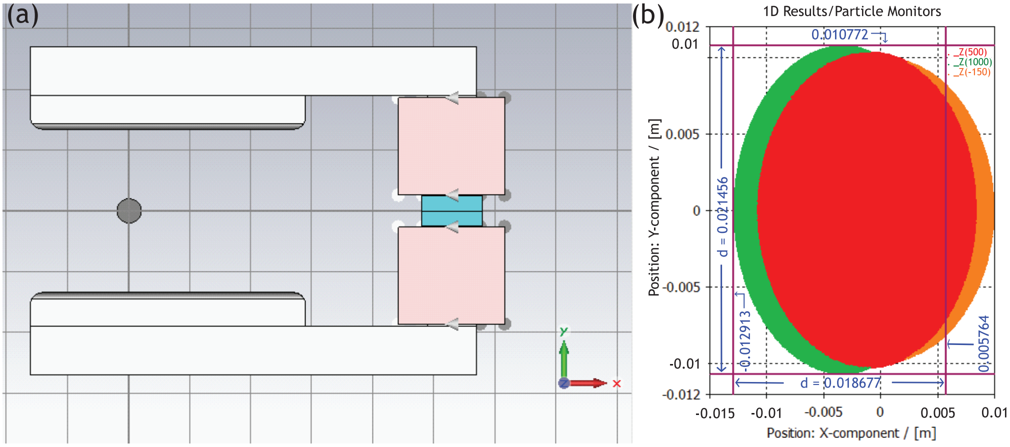
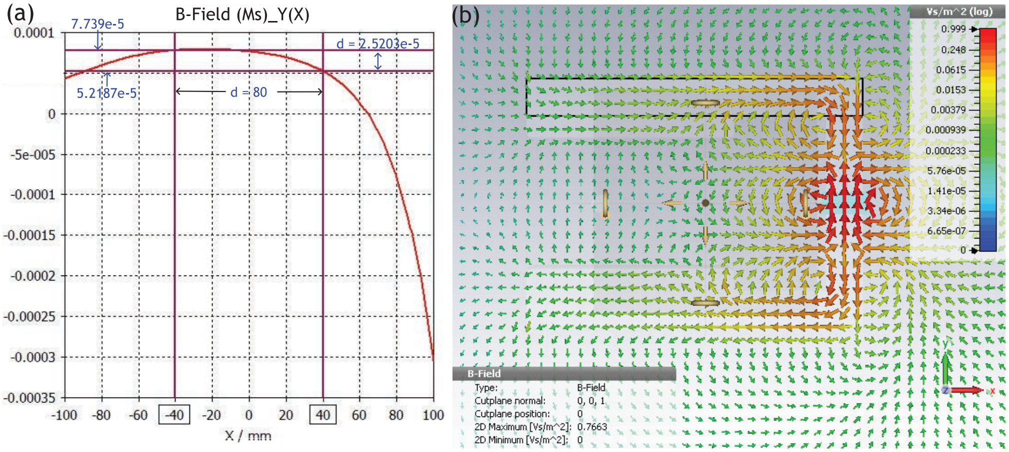


Figure 23.10: (a) C-shaped magnet design with two coils, and (b) Beam profiles at different distances.

- Current = 23.5A
- Number of Turns = 250 each
- Beam size : 14 mm × 26.6 mm at 1000
- Magnet : 50 mm × 50 mm × 12.5 mm, NdFeB 1.21 T
- Pole Width : 225 mm, Height 70 mm
- B_{max} at center = 0.7 Gauss
- Non-uniformity of field for -40 mm to 4 mm is 0.2 Gauss
- The Beam qualifying parameters at 1000 mm below magnet
- DF_x = (14-20)/20 = 0.3
- DF_y = (26.6-20)/20 = 0.333
- D_V = (26.6-20)/20 = 0.333

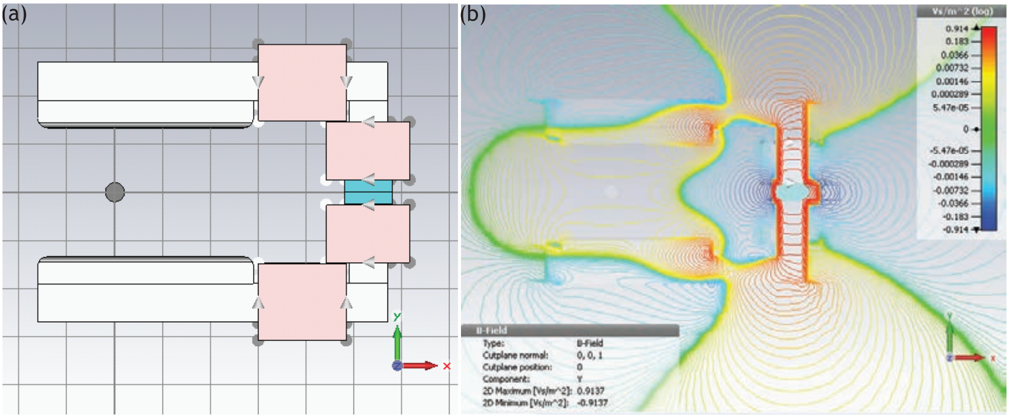
The Figs. 23.11 and 23.12 show the magnet design and field plots.



Type: B-Field
Cutplane normal: 0, 0, 1
Cutplane position: 0
2D Maximum [Vs/m^2]: 0.7663
2D Minimum [Vs/m^2]: 0

Figure 23.11: (a) B field in X direction, non-uniformity of field for ±40 mm is 0.3 Gauss, and (b) Field lines.

23.3.5 C-Shaped Core-02 (Finalized Design)



B-Field
Type: B-Field
Cutplane normal: 0, 0, 1
Cutplane position: 0
Component: Y
2D Maximum [Vs/m^2]: 0.9137
2D Minimum [Vs/m^2]: -0.9137

Figure 23.12: (a) C-shaped magnet design with four coils, and (b) Field line at Z = 0 when fields are compensated.

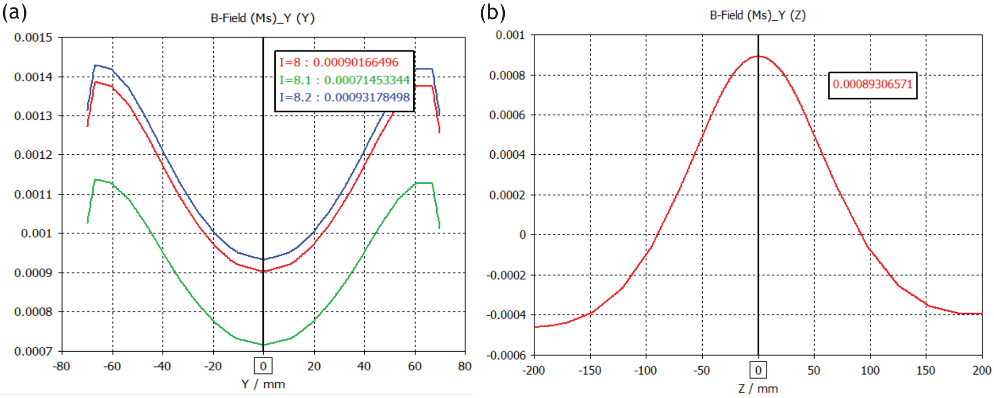


Figure 23.13: (a) Magnetic fields in Y direction, and (b) Field line along beam path direction (Z).

- Current = 8.2 A
- Number of Turns = 250,250,150,150
- Beam size : 14.9 mm × 25.5 mm at 1000
- Magnet : 50 mm × 50 mm × 12.5 mm, NdFeB 1.21 T
- Pole Width : 225 mm, Height 70 mm
- B_{max} at center = 8.9 Gauss
- Non-uniformity of field for -40 mm to 4 mm is 0.3 Gauss
- The Beam qualifying parameters at 1000 mm below magnet
- $DF_x = (14.9-20)/20 = -0.255$
- $DF_y = (25.5-20)/20 = 0.275$
- $D_V = (25.5-20)/20 = 0.275$

The Figs. 23.13 and 23.14 show the magnet design and field plots.

Conclusion:

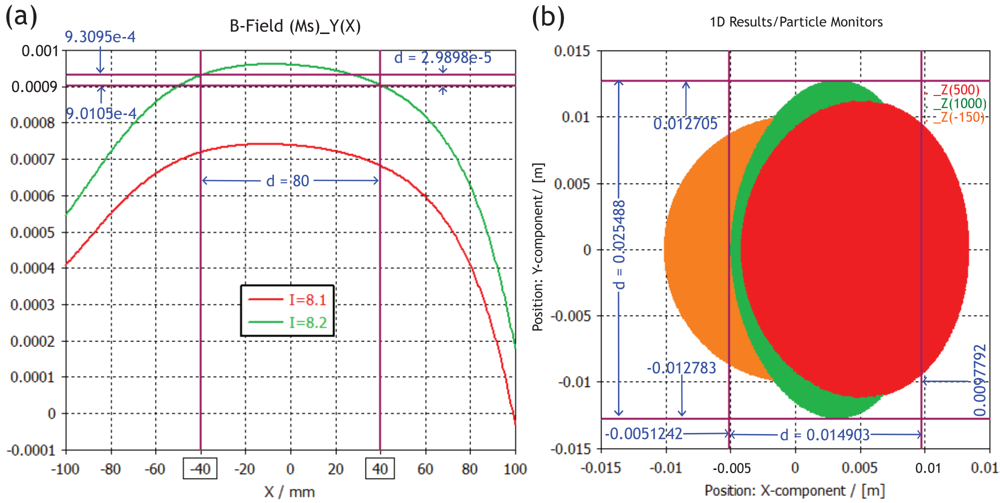


Figure 23.14: (a) Magnetic fields in X direction, and (b) Beam Profile at different Z, green (Z = 1000 mm), red (Z = 500 mm), Orange : input beam.

- Beam size : 14.9 mm × 25.5 mm at 1000 mm down
- Best possible design in the given condition of current within 10 A, large pole gap of 135 mm, C-shaped Dipole magnet and minimum non-uniformity
- Beam non-uniformity = 5 mm
- Uncompensated field : 170 Gauss
- Deflection expected : 40°

Note: In case of 100 kW EBWWT, the scan horn design does not permit for installation of window frame magnet.

23.4 Deflector Control Magnet Circuits

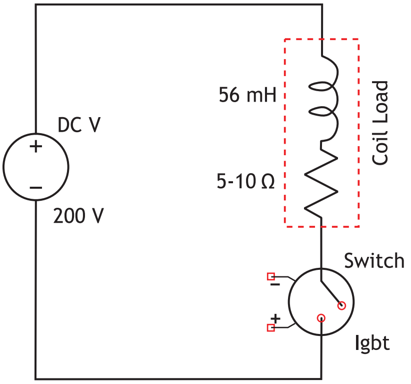


Figure 23.15: Circuit scheme.

X-Scan magnet gives two optical signal on its failure, one signal to 10 kHz inverter and another to deflector Magnet control Circuit. The optical signal trips the inverter by switching off the

IGBT's Driver. The signal to deflector magnet control circuit will initiate the actuation of deflector magnet to swipe the decaying high energy beam off the foil to the sides of the scan Horn. The optical signal is converted into electrical signal and given to Timer IC to get monostable pulse of fixed width. The pulse is decided by the RC value. The pulse is then given to Driver IC of IGBT. The Figs. 23.15 and 23.16 show the control circuit scheme and the control circuit respectively.

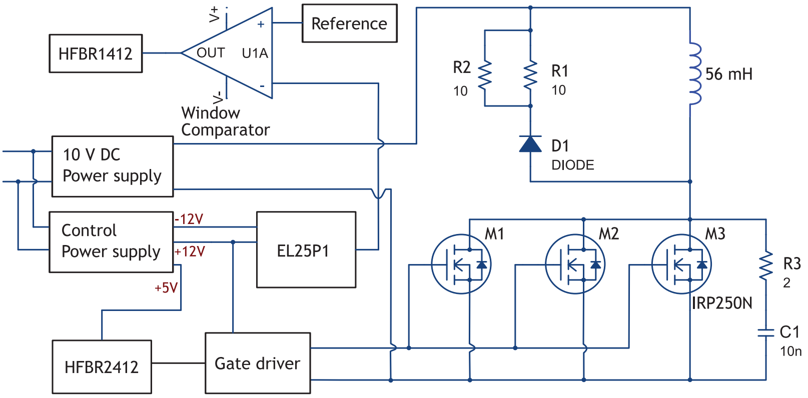


Figure 23.16: Control circuit.

23.5 Summary

- The compensated deflector magnet is Fail safe mechanism, will protect the accelerator even power shutdown happens.
- The magnet is designed and tested along with control circuit and field profiling. The time constant can be further reduced by increasing resistance in series with switch.
- The compensating magnet with both electromagnet and permanent magnet gives best uniformity for field and beam when coil is wound over the permanent magnet. But this scheme will have highest current requirement for compensation.
- The achieved uncompensated field in the designed magnet is 160 Gauss.

Suggestions for Further Reading

a) [121, 122]